

New flavor physics in b decays

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Abstract

A new $U(1)$ gauge boson coupling predominantly to the third family has been considered in connection with recent LEP data. We consider another likely consequence of such a gauge boson, a greatly enhanced b quark decay mode, $b \rightarrow s\nu_\tau\bar{\nu}_\tau$.

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Broken family gauge symmetries often arise in theories which seek to explain the masses of fermions in a dynamical framework. The lightest of these gauge bosons are expected to couple to the third family and not to the lighter families. Previously [1, 2], it was shown that the mixing of a such a massive $U(1)$ gauge boson (the X boson) with the Z causes shifts in the Z couplings to the third family. This leads to a distinctive pattern of universality-breaking corrections which is quite consistent with precision electroweak measurements. In particular the presently observed anomaly in R_b and the discrepancy between the values of α_s determined from R_ℓ and low energy measurements were shown to be natural consequences.

The X boson with coupling strength g_X receives a mass from the same source as the W and Z masses, and this immediately leads [1] to the relation¹

$$\left(\frac{g_X}{M_X}\right)^2 = \frac{G}{2\sqrt{2}}. \quad (1)$$

Results follow without requiring knowledge of M_X , although we may imagine M_X to lie in the several hundred GeV to 1 TeV range.

When the Z couplings to the third family are shifted by new flavor physics, then flavor changing vertices such as $Zb\bar{s}$, $Zd\bar{s}$ and $Zb\bar{d}$ may be generated by the effects of fermion mass mixing. The resulting flavor changing neutral currents from Z exchange were considered briefly in [1], and in more detail in [3]. Although very dependent on the nature of the fermion mass mixing, some of these effects may lie close to experimental limits.

In the present work we are instead considering the effect of a tree-level X -boson exchange, with the vertex $Xb\bar{s}$ generated via fermion mass mixing. This effect is not suppressed by the Z - X mixing amplitude, and would lead to the decays $b \rightarrow s\nu_\tau\bar{\nu}_\tau$ and $b \rightarrow s\tau\bar{\tau}$. These decays need only compete against the standard model $b \rightarrow c$ decay which is already suppressed by a small V_{cb} . Given the poor experimental limits on FCNC's involving the heavier quarks alone, it is even possible that these supposedly rare decay modes could occur at rates approaching the standard semileptonic b decay rate.

Indeed, there is some suggestion of a discrepancy between the observed experimental value of the semileptonic branching ratio of the B meson [4] and theoretical predictions of the same [5]. Related to this discrepancy are the indications that the charm multiplicity of the decay products is low [6]. Whether these discrepancies are a sign of new physics or are just a function of our poor understanding of the hadronic physics involved is still subject to debate [7, 8]. It should be noted that the Z - X mixing effect makes a low $\alpha_s(M_Z)$ in the 0.11 range more likely [1], and this in turn exacerbates the discrepancy in the semileptonic branching ratio [9].

¹More conservatively this could be taken as an upper bound on the coupling to mass ratio, since in principle there could be additional contributions to the X boson mass.

In [1] it was argued that the X -boson should couple to the following current ($R_\mu, L_\mu \equiv \gamma_\mu(1 \pm \gamma_5)/2$)²

$$J_\mu^X = \bar{t}(L_\mu - R_\mu)t + \bar{b}(L_\mu - R_\mu)b + \bar{\tau}(L_\mu + R_\mu)\tau + \bar{\nu}_\tau L_\mu \nu_\tau \quad (2)$$

with coupling strength g_X . Non-zero CKM matrix elements imply that there is mixing between quarks of different families, and we shall assume that some of this mixing happens in the down quark sector. This can be expressed in terms of the mixing matrices L^d and R^d which act on the mass eigenstate bases $(d, s, b)_L$ and $(d, s, b)_R$ respectively (such that the CKM matrix is $L^{u\dagger}L^d$). Then the X boson couplings to quarks contains the following $b - s$ transitions,

$$g_X X^\mu (\lambda_{23}^L \bar{s} L_\mu b - \lambda_{23}^R \bar{s} R_\mu b + \text{h.c.}), \quad (3)$$

where $\lambda_{ij}^L \equiv L_{3i}^{d*} L_{3j}^d$ and $\lambda_{ij}^R \equiv R_{3i}^{d*} R_{3j}^d$.

It is worth noting that there are no significant experimental constraints on FCNC's involving just the second and third generation quarks. This is in contrast to the very strong constraints on FCNC's involving the d quark. We shall henceforth assume that the 13 and 12 components of λ^L and λ^R are very small as required; of more interest to us are the much less constrained 23 components.

The interesting decays mediated by the X boson are $b \rightarrow s\nu_\tau \bar{\nu}_\tau$ and $b \rightarrow s\tau\bar{\tau}$. The decay $b \rightarrow s\tau\bar{\tau}$ is suppressed by phase space compared to the decay $b \rightarrow s\nu_\tau \bar{\nu}_\tau$; we estimate the ratio of the $\nu_\tau \bar{\nu}_\tau$ rate to the $\tau\bar{\tau}$ rate to be about 4.5 for $m_b = 4.5 \text{ GeV}$ and about 2.5 for $m_b = 4.8 \text{ GeV}$. Furthermore reconstruction of the $\tau\bar{\tau}$ decay mode is challenging, making a clear experimental signature difficult. A possible exception is when both τ 's decay leptonically, leading to $B \rightarrow X_s \ell^+ \ell^- + (\text{missing energy})$ with $\ell = e, \mu$.

In the following we will concentrate on the $b \rightarrow s\nu_\tau \bar{\nu}_\tau$ mode. In the standard model this mode proceeds via penguin diagrams with a virtual Z boson and box diagrams involving W bosons. The predicted branching ratio for this process is about 5×10^{-5} [10, 11]. Presently there appear to be no significant experimental bounds [4].

The X boson induces the following effective four-fermion interaction.

$$(g_X/M_X)^2 (\lambda_{23}^L \bar{s} L_\mu b - \lambda_{23}^R \bar{s} R_\mu b) \bar{\nu}_\tau L^\mu \nu_\tau \quad (4)$$

The contribution of this term to the decay rate is

$$\Gamma(b \rightarrow s\nu_\tau \bar{\nu}_\tau) = (|\lambda_{23}^L|^2 + |\lambda_{23}^R|^2) G^2 m_b^5 / 12288 \pi^3. \quad (5)$$

Eq. (1) has been used and m_s has been ignored.

²In [1, 2] a reversed, nonstandard definition was assumed.

We may compare to the semileptonic width of the b and include QCD corrections to obtain

$$\frac{\Gamma(b \rightarrow s\nu_\tau\bar{\nu}_\tau)}{\Gamma(b \rightarrow ce\nu)} = \frac{|\lambda_{23}^L|^2 + |\lambda_{23}^R|^2}{64|V_{cb}|^2 g(\frac{m_c^2}{m_b^2})} \left[\frac{1 - \frac{2\alpha_s(m_b)}{3\pi} f(0)}{1 - \frac{2\alpha_s(m_b)}{3\pi} f(\frac{m_c}{m_b})} \right] \quad (6)$$

where $f(x)$ and $g(x) = 1 - 8x + 8x^3 - x^4 - 12x^2\ln(x)$ are found in [12]. For example, with $m_b = 4.8 \text{ GeV}$ and $m_c = 1.5 \text{ GeV}$, $|\lambda_{23}^L|^2 + |\lambda_{23}^R|^2 \approx 30|V_{cb}|^2$ would give a $b \rightarrow s\nu_\tau\bar{\nu}_\tau$ branching ratio equal to the semileptonic branching ratio of b quarks. Mixing angles of this size in the down quark sector may be somewhat larger than expected, but are not entirely unreasonable. If they were this large they would be sufficient to account for the possible discrepancy in the semileptonic branching ratio. This is because the new decay mode would increase the total width of the b such as to decrease the semileptonic branching ratio by 10 or 15 percent.

We consider $B\bar{B}$ production in e^+e^- collisions, with one of the B mesons decaying through $b \rightarrow s\nu_\tau\bar{\nu}_\tau$. This strange quark should hadronize into an energetic K or K^* a large fraction of the time. One then observes an energetic strange meson, a number of other particles from the decay of the second B meson and a large amount of missing energy and momentum. We note that since there are two neutrinos in the event, the quantity $E_{miss}^2 - |\vec{p}_{miss}|^2$ should not peak near zero, unlike the case of only one neutrino. After identifying the energetic strange meson, the second B meson may be reconstructed from its decay products if it decays purely hadronically. For this one may require that there be no charged lepton in the event. A veto on events where the energetic strange meson arises from a displaced vertex due to a charm meson could also be useful. In the case that the two B mesons are produced close to rest, such as at CLEO, the energetic K or K^* would recoil against the total missing momentum of the event. In the other case when the B mesons are energetically produced, the K or K^* will be clearly isolated from the decay products of the second B .

The other main effect of nonvanishing λ_{23}^L and λ_{23}^R occurs in $B_s - \bar{B}_s$ mixing. The main contribution of the X boson comes from the operator

$$\frac{(\lambda_{23}^L + \lambda_{23}^R)^2}{8} \frac{g_X^2}{M_X^2} \bar{s}\gamma^\mu\gamma^5 b \bar{s}\gamma^\mu\gamma^5 b + \text{h.c.}, \quad (7)$$

which gives a mass mixing of order

$$\Delta M_{B_s} \approx G f_{B_s}^2 M_{B_s} |\lambda_{23}^L + \lambda_{23}^R|^2 / 8\sqrt{2}. \quad (8)$$

The only experimental result comes from time dependence of $B_s - \bar{B}_s$ mixing using dileptons, which yields $\Delta M_{B_s} > 1.2 \times 10^{-12} \text{ GeV}$ [4]. The standard model result is larger, $\Delta M_{B_s} = (1 \pm .5) \times 10^{-10} \text{ GeV}$ [13], while the X boson contribution with $|\lambda_{23}^L + \lambda_{23}^R| = 2|V_{cb}|$ is larger still, $\Delta M_{B_s} \sim 10^{-9} \text{ GeV}$. This provides additional incentive to try to get some experimental

handle on $B_s - \overline{B}_s$ mixing. We note that a similar argument using the observed size of $B_d - \overline{B}_d$ mixing produces the very tight constraint $|\lambda_{13}^L + \lambda_{13}^R| < 0.002$ (with a weaker constraint on $|\lambda_{13}^L - \lambda_{13}^R|$).

If there is mixing in the charged lepton sector, then besides $b \rightarrow s\tau^-\tau^+$ there could also be X boson contributions to $b \rightarrow s\tau^-l^+$ and $b \rightarrow sl^-l^+$ ($l = e, \mu$). These contributions are naturally small since the vertices involved bring in additional small mixing angles. For example if mixing in the lepton sector was similar to the mixing in the quark sector then a suppression of order $|V_{cb}|^4$ for $b \rightarrow sl^-l^+$ relative to $b \rightarrow s\nu_\tau\overline{\nu}_\tau$ would not be surprising. The upper limits from CLEO[14] are $BR(B \rightarrow K^*e^+e^-) < 1.9 \times 10^{-5}$, $BR(B \rightarrow K^*\mu^+\mu^-) < 3.9 \times 10^{-5}$ and $BR(B \rightarrow K^*e^+\mu^-) < 1.8 \times 10^{-5}$. Similarly CDF quotes an upper limit of $BR(B \rightarrow K^*\mu^+\mu^-) < 5.1 \times 10^{-5}$ [15]. The standard model predictions for these are of order 5×10^{-6} [10].

In conclusion we have given some motivation for imagining that certain “rare” decay modes of the b quark may in fact be very substantial decay modes. Our speculations tie in closely with the hints of new flavor physics presently emerging from LEP.

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